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Storing CO_2 underneath the Siberian Permafrost: A win-win solution for long-term trapping of CO_2 and heavy oil upgrading

Yves-Michel Le Nindre[a]*, Delphine. Allier[a], Albert. Duchkov[b], Liubov K. Altunina[c] Stepan Shvartsev[b], Mikhail Zhelezniak[d], and Jean Klerkx[e]

[a] *BRGM, Orléans, France*
[b] *IPGG, Trofimuk Institute of Petroleum Geology and Geophysics, Tomsk and Novosibirsk branches, Russia*
[c] *IPC, Institute of Pertoleum Chemistry, Tomsk, Russia*
[d] *Melkinov Permafrost Institute, Yakutsk , Russia*
[e] *IBES, International Bureau for Environmental Studies, Brussels, Belgium*

Abstract

A two-year project entitled "Assessment of the Feasibility of CO_2 Storage in the Russian Permafrost" was carried out in Russia in collaboration with the Siberian branch of the Russian Academy of Sciences. This project delivers new conclusions about the safety role of the permafrost and specific conditions of storage in an area of abnormal geothermal gradient in Western Siberia. One of the specific issues of the project was the potential formation of carbon dioxide hydrates from the injected CO_2 and the possible reaction between the existing methane hydrates and the injected CO_2. Maps have been constructed showing the areas of CO_2 hydrate stability. A second specific issue was the compatibility of CO_2 storage in the permafrost with oil production. Pilot tests of EOR technologies, involving either the injection of CO_2 or the generation of CO_2 in situ, proved very efficiency for high-viscosity oil pools. Therefore, we propose to inject CO_2 in West Siberia into high-viscosity oil fields. High-viscosity oil fields are mainly located in the centre of the Western Siberian Basin in Khanty-Mansijsk autonomous okrug (KMAO). An alternative or complementary solution is storage in aquifers. Deep aquifers, such as the Pokur formation overlain could also be storage targets, but their potential is unknown because they have not been explored in detail. The inventory of major CO_2 sources in Western Siberia has shown that the major CO_2 emission in the power sector comes from the KMAO, where power stations in Surgut and Nizhnevartovsk are large CO_2 sources. GIS mapping of the permafrost depth and thickness, and the associated stability domain of the CO_2 hydrates, has shown that a good overlap could exist between these industrial areas and the stability domain of the gas hydrates, underneath the permafrost. Storage beneath the permafrost as CO_2 hydrate is not suitable due to the probable rapid plugging of the porosity by solid gas hydrates. But, the CO_2 should be stored at supercritical state in the hydrocarbon fields, with added value of heavy oil upgrading, and trapped underneath a classical cap rock. In addition, the permafrost would act as a secondary cap-rock by trapping the CO_2 as hydrates if the primary caprock should fail.

Key words: Carbon capture and storage; Carbon emssion source; Storage Potentials; Permafrost, Gas hydrates, Heavy oil fields, Russia, Siberia

* Corresponding author. Tel.: +33 2 38 64 3496; fax: +33 2 38 64 3575.
E-mail address: ym.lenindre@brgm.fr.

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1. Introduction

The northern territories of Russia present a specific property related to the safe storage of CO_2. These territories are underlain by permafrost, a permanent frozen upper layer that may act as an adequate seal for maintaining CO_2 in the underground. Another possible advantage of the permafrost is that because of the low temperatures, methane and even CO_2 gases are stable in solid form, as so-called gas hydrates.

Under the auspices of INTAS[2], a two-year project entitled "Assessment of the Feasibility of CO_2 Storage in the Russian Permafrost" was carried out in Russia in collaboration with the Siberian branch of the Russian Academy of Sciences [1] Le Nindre and Allier (2009).

The purpose of the project is to assess the feasibility and capacity of CO_2 storage in the northern territories of Russia underlain by permafrost. Based on the experience that has been gained by EC projects in the investigation of experimental sites for CO_2 storage, it will assemble information on the particular conditions of the permafrost, and it will evaluate how these conditions will influence - in a positive or a negative way - the process of CO_2 storage. Considering that the northern territories of Russia are the site of intense oil and gas exploitation, the project also studies the compatibility of CO_2 storage with the oil industry.

2. Major carbon emission sources in Western Siberia

Information as locations, type of industrial sector, yearly amount of the main product of the plant, has been collected on CO_2 sources emitting more than 100,000 tons CO_2/year.

The inventory of major CO_2 sources in Western Siberia has shown that the major CO_2 emission in the power sector (36 Mt/a) comes from the Khanty-Mansijsk autonomous okrug (KMAO, 37 Mt, 23% of total Siberian emissions), where power stations in Surgut and Nizhnevartovsk are large CO_2 sources (Figure 1and Table 1). It is found that power-related CO_2 emissions exceed those caused by burning oil gas in torches in the KMAO oil field [2] (Dushina *et al.*, 2007) The second place among West–Siberian regions is the Kemerovo region (20 Mt, 13% of Siberian emissions), associated with large production of cement (0.9 Mt) and nitrogen fertilizer and with coal-fired power stations in Belovo, Novokuznetsk, Osinniki (18 Mt).

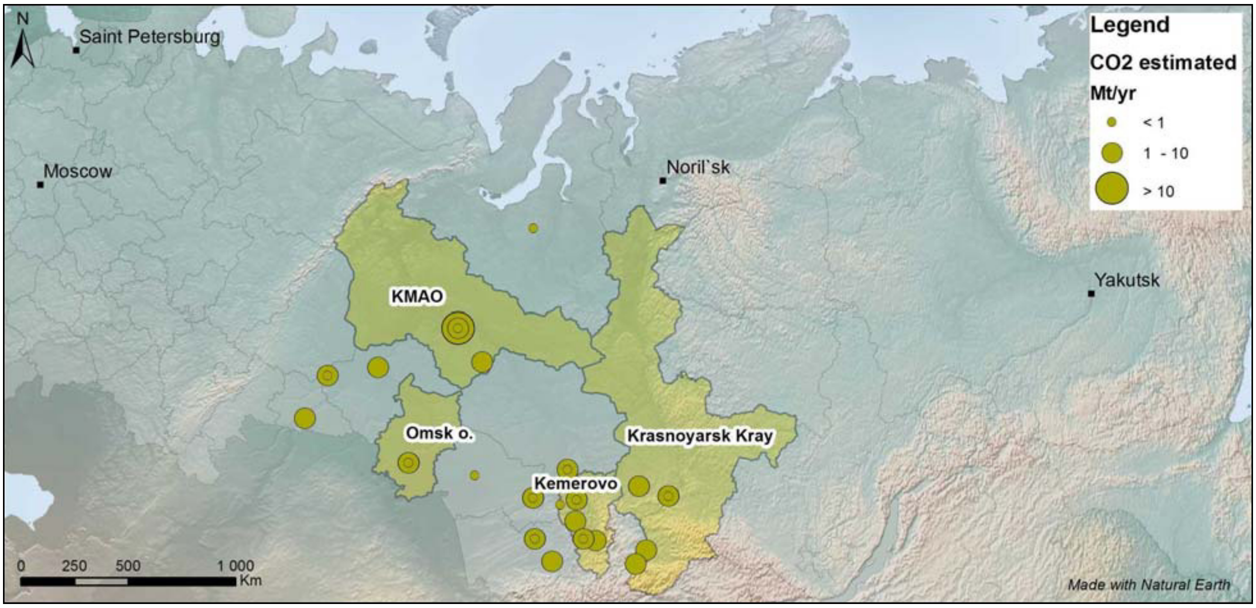

Figure 1 CO_2 sources emitting more than 100 000 tons CO_2/year, in Siberia (Russia).

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[2] International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union. Project n° 06-100025-9220.

Table 1 Large CO_2 Sources and Emissions by sector in Siberia

Region	City	Sector	Plant name	CO_2 estimated (Mt CO_2/yr)
Khanty-Mansijsk Okrug	Surgut	Power	SURGUT TETS-2	**23.5**
	Surgut		SURGUT TETS-1	7.5
	NizhneVartovsk		NIZHNE-VARTOVSK TETS	5.4
			Subtotal	*36*
	Surgut	Refineries	SURGUT NPZ	0.8
			Total	37
Kemerovo region	Mezhdurechensk	Power	TOM-USA TETS	5.4
	Belovo		BELOVO TETS	5.2
	Novokuznetsk		ZAPADNO SIBIRSKAYA TETS	2.2
	Novokuznetsk		YUZHNO-KUZBAS TETS	1.9
	Kemerovo		NOVO-KEMEROVO TETS	1.8
	Kemerovo		TSENTRALNAYA TETS	1.6
	Kemerovo		KEMEROVO TETS	0.3
			Subtotal	*18*
	Kemerovo	Ammonia	AZOT	0.9
	Novokuznetsk	Cement	Kuznetsky Cement Works	0.4
	Yashkino		Yashkin Cement Works	0.4
			Total	*20*
Omsk region	Omsk	Power	OMSK-5	6.7
	Omsk		OMSK-3 REPOWER	0.4
	Omsk		OMSK TETS	2.8
	Omsk		OMSK-4	2.3
	Omsk		OMSK-6	1.4
	Omsk		OMSK-3	1.0
			Subtotal	*15*
	Omsk	Refineries	OMSK NPZ	5.5
	Omsk	Ethylene	OMSK ETHYLENE	0.3
			Total	*23*

3. Characterization of the permafrost

This two-year project delivers new conclusions about the safety role of the permafrost and specific conditions of storage in an area of abnormal geothermal gradient in Western Siberia.

Data on the physical parameters of the permafrost have been collected, related to 400 boreholes in 375 locations. The data concern: coordinates, depth to the upper and lower boundaries of permafrost, thickness, temperature at depths of 20 m, 500 m, 1000 m and 2000 m.

Thermal, physical and chemical properties of the permafrost are defined. Spatial variations in its properties indicate advantages/disadvantages of the permafrost as a site for CO_2 storage.

3.1. General properties

Permafrost is present up to the surface north of 61° N. The permafrost reaches a thickness of 500-600 m in the Far North (Figure 2). This part of West Siberia permafrost is the most suitable for CO_2 sequestration. The monolithic structure of the permafrost guarantees the sealing effect for CO_2.

South of 66-65° N relict (buried) permafrost exists. The permafrost is locally disrupted; it is discontinuous and occurs as islands separated by thawed rocks (taliks). The relict permafrost is not a monolithic shielding body.

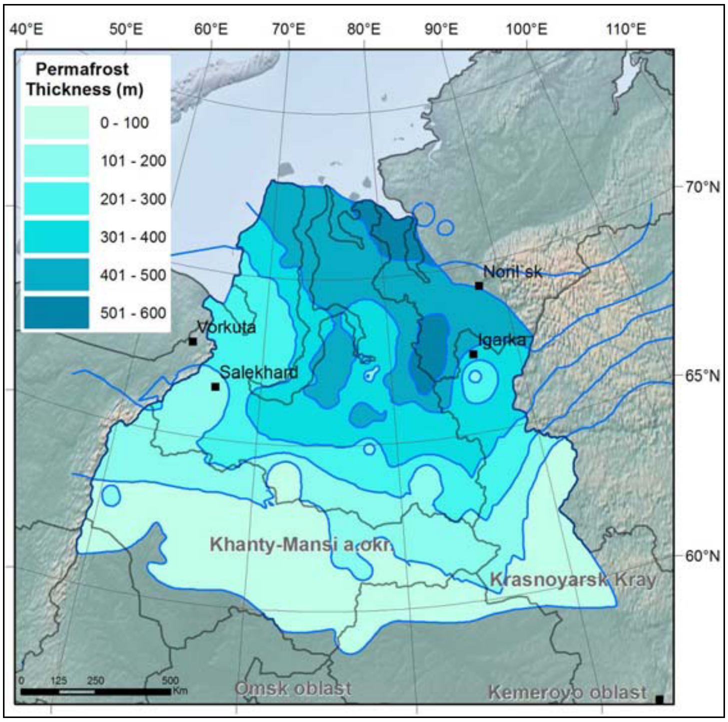

Figure 2 Thickness of permafrost in Western Siberia

The depth of the permafrost is controlled by the geodynamic context and the rock type. The depth of the top boundary of permafrost is the result, in the south of the western Siberia, of the formation of burial (relict) permafrost during the last 6-5 thousand years (Figure 3). The position of the bottom boundary of permafrost is determined by paleo conditions of cold epoch (Sartanian period 20-15 thousand years ago) and modern heat flow. Its displacement upwards is extremely slow.

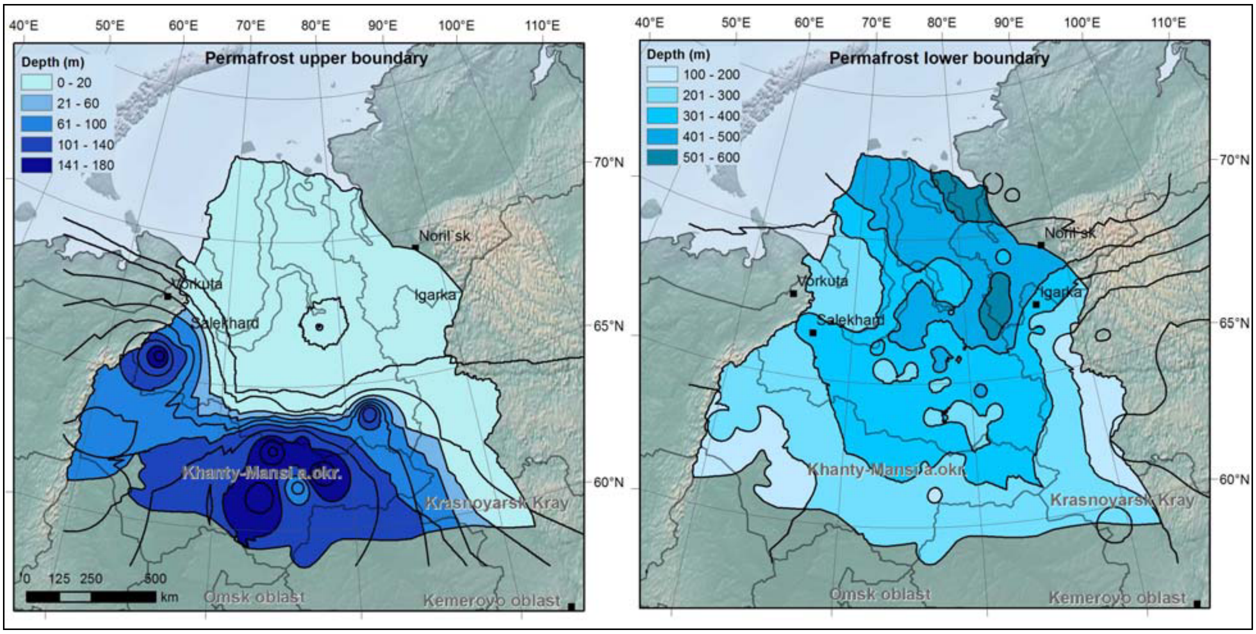

Figure 3 Upper and lower boundaries of permafrost in Western Siberia

3.2. Thermal properties

Stable and instable permafrost were characterised by their geothermal profiles, by their present geometry, especially in western Siberia ([3] Duchkov *et al.*, 2008), and by their kinetics of recession ([4] Spektor *et al.*, 2007).

3.3. Assumed effect of CO_2 injection in the permafrost, gas hydrates

One of the specific issues of the project was the potential formation of carbon dioxide hydrates from the injected CO_2 and the possible reaction between the existing methane hydrates and the injected CO_2 ([3] Duchkov *et al.*, 2008) (Figure 4).

The highest quantity of CO_2 can be injected at the liquid and super-critical state of carbon dioxide. Physical conditions of liquid CO_2 exist at depth of more than 700-1500 m and temperature as less as 10-20°C, namely in the polar regions of Western and Eastern Siberia predominantly, and in western regions of the Sakha Autonomous Republic.

The solubility of CO_2 injected in aquifers is 2-3 times higher in permafrost regions due to the low temperature: from 10-20 (at the depth of 100m) up to 12-44 (at the depth of 2.5km) l CO_2/l H_2O (average, ~1 mol/l).

The potential reaction of CO_2 with reservoir rocks is assumed at about 7-20 kg of gas per 1 m^3 of rock. In low-temperature conditions of permafrost regions the chemical binding of CO_2 will proceed 2-3 times slower.

At the time of the injection of CO_2 in the permafrost, two problems may arise: ground thawing and displacement of methane bound in gas hydrates. Indeed, the formation of gas hydrates is an exothermic process: by the formation of 1 kg of gas hydrate, 390 kJ is released, i.e. the quantity of heat required to thaw about 1 kg of ice (330 kJ/kg). But the cryotropic potential of the permafrost is sufficient for absorption of the heat released at the formation of new hydrates.

Carbon dioxide hydrates are stable under milder thermobaric conditions as compared with methane hydrates.

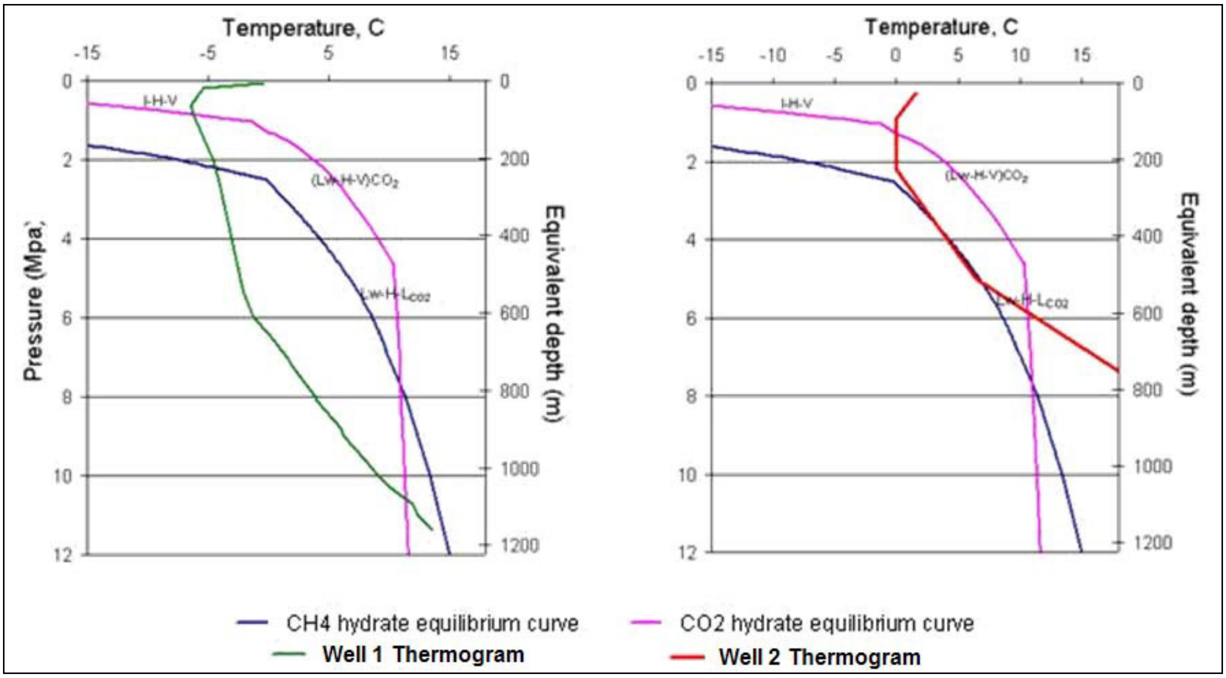

Figure 4 Equilibrium conditions curves of gas hydrates and two examples of well's thermograms (Estimation of CO_2 and CH_4 hydrates stability zones using the intersections on thermograms and equilibrium curves)

Therefore, an important zone of the permafrost falls in the thermobaric stability field for CO_2 hydrates. Maps have been constructed showing the areas of CO_2 hydrate stability.

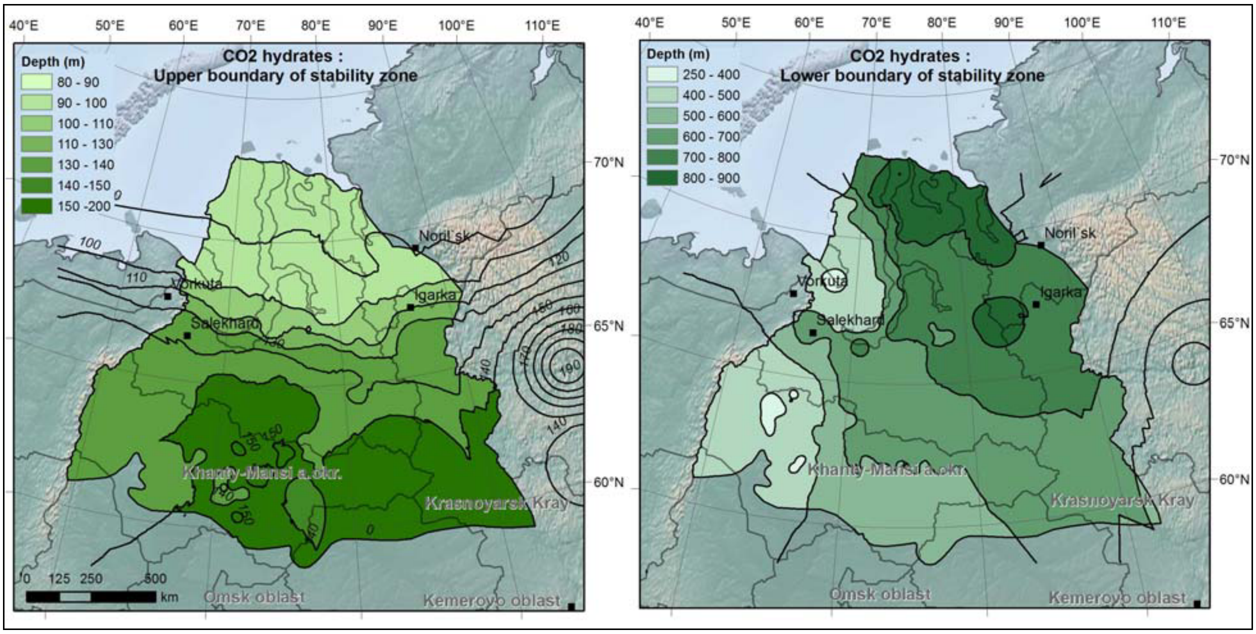

Figure 5 Upper and lower boundaries of stability zone of CO_2 hydrates in Western Siberia

In addition, in the presence of a sufficient amount of water, which is the case of the permafrost, hydrocarbon gases and carbon dioxide form mixed hydrates. Their stability is considerably higher than hydrates of individual gases. Thus, the injection of CO_2 into permafrost should result in the increase in gas hydrate stability, which is an additional safety condition for CO_2 injection.

Wells in the area of the Ob River gulf, demonstrate the occurrence of ice and gas hydrates in shallow gas condensate fields trapped in the permafrost, and the upward shift of the isotherms by the sea (Figure 6).

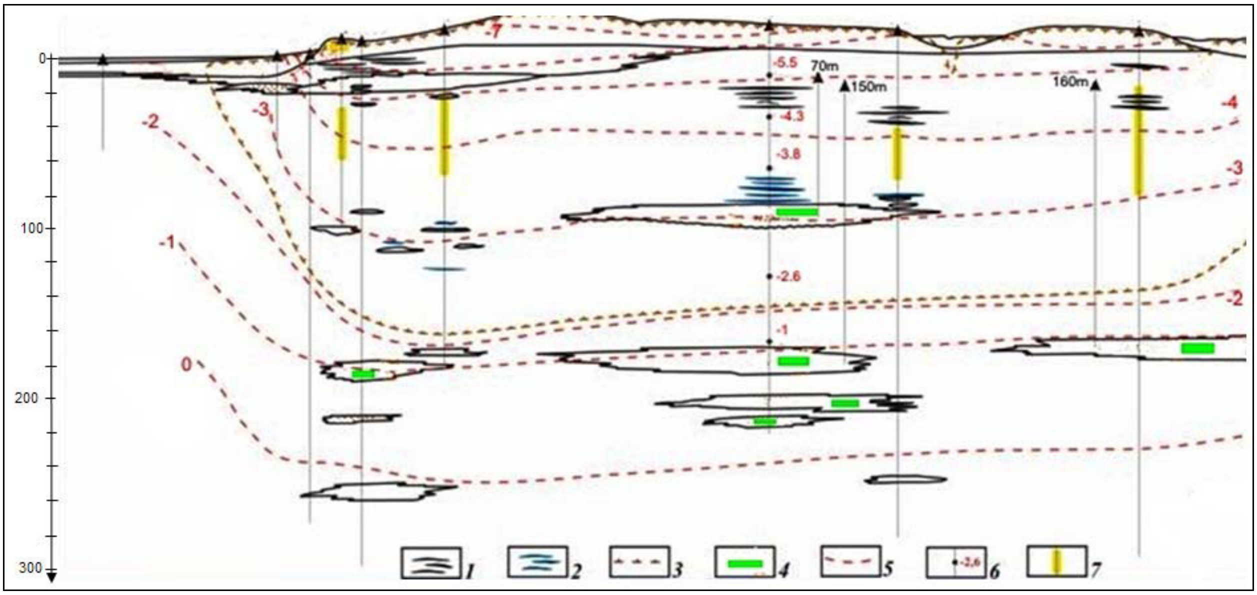

Figure 6 A schematic section of permafrost thickness of the Harasaveyskoe gas-condensate field ([5]Novikov, 2007, modified from Badu, 2005) 1 – ice and ice-soil bedding (on geophysical data); 2 – ice gas hydrated bedding (on geophysical data); 3 – border of permafrost distribution; 4 – pressure and non-pressure cryopegs in sandy rocks; 5 – an isotherms 0°C and isotherms below 1 – 7 °C; 6 – temperature in wells with standing 1 – 2 years; 7 – intervals of gas kick at drilling.

3.4. Consequences of oil industry for permafrost

The only effect of the activities of the oil industry on the permafrost is related to borehole drilling. Well drilling through the permafrost leads to thawing resulting in cavern formation and well-mouth erosion. However, the effects are limited to the very upper part of the permafrost, and are restricted to the emplacements of boreholes.

Since 95 % of oil fields in West Siberia are being developed by flooding, the injection of CO_2 is compatible with the existing technologies used oil production. It was shown that oil viscosity considerably decreases at the increase of the pressure of oil saturation with CO_2 and increased content of CO_2 in oil fields [6] (Altunina and Kuvshinov, 2007).

Pilot tests of EOR technologies, involving either the injection of CO_2 or the generation of CO_2 in situ, proved very efficiency for high-viscosity oil pools [7] (Altunina, 2007). Therefore we propose to inject CO_2 in West Siberia, namely into oil high-viscosity oil fields. This is a method intended to enhance oil recovery at different stages of development, including at a later stage, i.e. for partially depleted oil fields.

Oil production is fully compatible with permafrost.

4. CO_2 storage potential

4.1. Storage in hydrocarbon fields

High-viscosity oil fields are mainly located in the centre of the Western Siberian Basin in Khanty-Mansiysky autonomous okrug (32 oil fields) [8] (Polishchuk and, Yashchenko 2007). . The distribution of these oil fields among oil-and-gas-bearing regions (OGR) is as follows: 50% in Srednesibirskaya OGR, 25% in Kaymysovskaya OGR, 12.5% in Priuralskaya OGR, and the rest in Vasyuganskaya OGR and Nadym-Purskaya OGR. High-viscosity oils are heavy, sulfurous, tarry, but low-waxy and low-asphaltene oils with a lower content of fractions with an overpoint of 200°C.

4.2. Storage in aquifers

An alternative or complementary solution is storage in aquifers. Deep aquifers, such as the Pokur formation overlain by the Kupnetsov formation as cap rock, could also be storage targets, but their potential is unknown because they have not been explored in detail.

Conclusions

GIS mapping of the permafrost depth and thickness, and the associated stability domain of the CO_2 hydrates, has shown that a good overlap could exist between the industrial areas and the stability domain of the gas hydrates, underneath the permafrost (Figure 7). Therefore, assuming that storage beneath the permafrost as CO_2 hydrate is not suitable due to the probable rapid plugging of the porosity by solid gas hydrates, the CO_2 should be stored at supercritical state in the hydrocarbon fields, with added value of heavy oil upgrading ([9] Altunina *et al.*, 2007), or deep aquifers, and trapped by a confining bed. The isotherms at different depths delineate the domain matching the two conditions of supercritical CO_2 (below) and of gas hydrates (above). In the case where the first confining bed fails, the permafrost will act as a secondary cap-rock by trapping the CO_2 as hydrates. The results of the project are available at: http://www.ibes.be/permafrost/HTML/data1.htm.

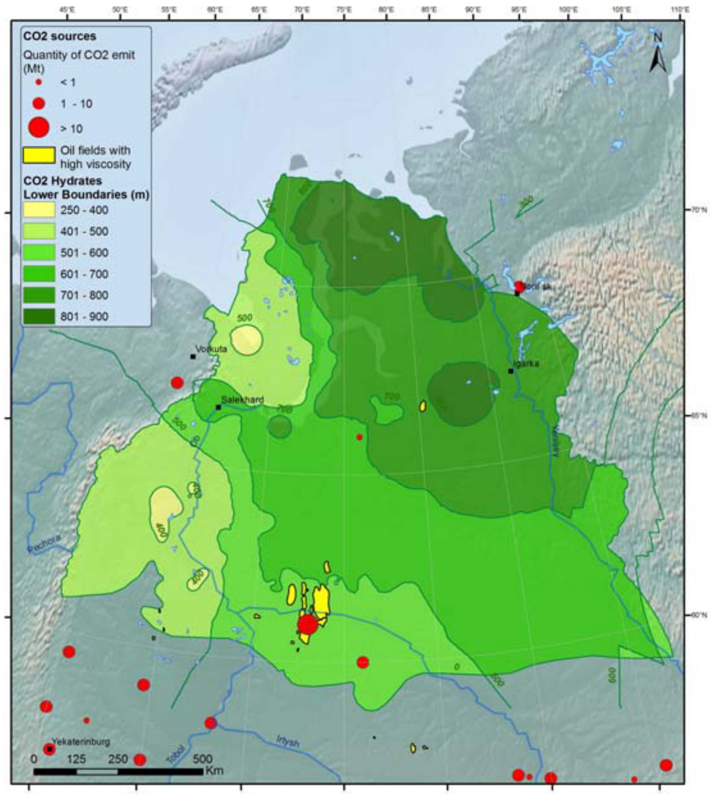

Figure 7 Location of heavy oil HC fields, major industrial CO_2 sources and gas hydrates stability zone in Western Siberia

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